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RECENT DEVELOPMENTS IN PRESSURE ALTIMETRY

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Abstract

Some of the more significant accomplishments of recent years relating to the improvement of instruments, the measurement and compensation of the errors of static-pressure systems, and the collection of information on the flight technical error are reviewed. Previous studies of the relation between altimetry errors and vertical separation standards are discussed and the problem of assessing vertical separation standards is examined from an approach different from that used in those studies. On the basis of the present review, the need for further work is indicated for standardizing the calibrations of static-pressure systems, for collecting additional information on the flight technical error, for developing an altitude-deviation monitoring and warning device, and for improving the maintenance practices relating to the testing and installation of the instruments. author

Introduction

A knowledge of the altimetry errors that determine the degree to which aircraft adhere to their assigned altitudes is needed for assessments of the adequacy of vertical separation standards. For cruise or holding flight, the extent to which an airplane deviates from its assigned altitude depends on the system error (combined instrument and static-pressure errors) and on the flight technical error (random deviations of the airplane from its cruise flight level). See figure 1.

For a great many years extensive efforts have been made by manufacturers, operators, and government agencies to improve the accuracy of instruments and static-pressure systems and to collect data on the flight technical error. In addition, analytical studies have been conducted by several organizations - notably ICAO (International Civil Aviation Organization) and IATA (International Air Transport Association) - to estimate the altimetry error (combined system and flight technical errors) for an evaluation of vertical separation standards (refs. 1 to 4).

In the present paper, some of the more important developments relating to the instrument, static-pressure and flight technical errors will be reviewed and the problem of assessing separation standards will be examined by an approach different from that used in other studies.

Glossary of Terms

Instrument error - statistical sum of the errors due to the mechanical imperfection of the altimeter (i.e., scale or diaphragm, hysteresis, drift, friction, temperature, instability, and backlash) and the errors due to readability (altitude and barometric-setting scales).

Static-pressure error - the difference between free-stream static pressure and the pressure registered by the aircraft static-pressure source (static-pressure tube or fuselage vent); for a given airplane, the statistical sum of the fixed error (the error applicable to the aircraft type) and the variable error (the probable departure of the actual error from the fixed error).

Flight technical error - random deviations of an airplane from its cruise flight level.

System error - statistical sum of the instrument error and the static-pressure error.

Altimetry error - statistical sum of the system error and the flight technical error.

σ - standard deviation of an error.

3σ - probable maximum value of an error or the value having a probability of 99.7 percent.

Instrument Errors

Significant reductions in the instrument errors have been achieved through improvements in the design of the instruments and the test equipment used to calibrate the instruments.

Improved instrument design led to the development of the "precision" altimeter (refs. 5 and 6) having low hysteresis and a high degree of repeatability (ref. 7) and, in addition, scale (or diaphragm) errors which are less than one-half those of the older "sensitive" altimeter (refs. 8 and 9). Further reductions in the scale errors of the precision altimeter have been made possible by the development scale-error correction devices (ref. 10). As an indication of the extent to which the instruments have been improved, the instrument error of a precision altimeter with scale-error correction was estimated in reference 1 to be 132 feet at 40,000 feet as compared to 663 feet for the sensitive altimeter without scale-error correction. Note that these figures are 3σ values where σ is the standard deviation of the errors.

Improvements in the calibration test equipment have produced a variety of precision barometers and manometers that permit calibrations to be performed to an accuracy of 0.005 inch of mercury or 5 feet at sea level (refs. 11 and 12). For the routine testing and adjustment of altimeters, however, this accuracy is not always realized in practice. In a recent survey of test equipment in control towers and instrument repair shops, for example, it was found that many control towers work to a tolerance of only 0.02 inch of mercury and that only 7 of the 37 barometers tested in the repair shops conformed to a tolerance of 0.005 inch of mercury (ref. 13). This survey also disclosed other deficiences in the test equipment and a lack of standardization in the laboratory test procedures. In two surveys of scale-error tolerances and installation errors of altimeters in operational use, deficiencies relating to the installation and maintenance of the instruments were also uncovered (refs. 14 and 15). On the basis of these surveys, it would appear that further efforts are required to bring the competence level of instrument maintenance practices up to that which has been achieved in the development of the instruments and test equipment.

Static-Pressure Errors

The static-pressure error of an airplane is considered by ICAO and IATA as comprising a fixed error (the error applying to the aircraft type) and a variable error (the probable departure of the actual error of the airplane from the fixed error). The variable error is considered to be a composite error that results from differences in the errors among aircraft of a type, the errors of the calibration procedure, and the change in the error during the service life of the airplane.

The Fixed Error

For a given aircraft configuration, the magnitude of the fixed error depends on the design and location of the static-pressure sensor (fuselage vent or boom-mounted static-pressure tube) and on Mach number and angle of attack. For fixed errors exceeding 50 feet, both ICAO and IATA recommend that corrections be applied. If the corrections are applied with calibration cards, the residual error is estimated to be 15 feet for piston-engine aircraft and 50 feet for jet aircraft; if the corrections are applied by servo-correction devices, the residual error is given as 15 feet (refs. 1 and 2). However, in view of the specified accuracy of present-day air data compensators (i.e., 0.2 percent of the altitude or, for example, 80 feet at 40,000 feet - ref. 16), the 15-foot value given in references 1 and 2 would appear to be overly optimistic.

For operations in the lower subsonic speed range, the magnitude of the fixed error of many installations is either sufficiently small as to require no correction or the calibration is sufficiently simple that corrections can be applied with calibration cards. For aircraft operating at high subsonic speeds, however, the variation of the error with Mach number and angle of attack is generally of such magnitude and complexity as to require correction by automatic means. For supersonic flight, the fixed error of a fuselage-nose installation will be smaller than that of any other conventional installation (ref. 17). However, as noted in reference 18, even though the error of this installation may be small in terms of pressure, the corresponding error in terms of altitude will probably be of such magnitude as to require compensation. In a recent calibration of a fuselage-nose installation on the X-15 airplane, for example, the static-pressure error at a Mach number of 3.1 was found to be only 3/4 percent of the impact pressure but the corresponding altitude error was 2,200 feet (ref. 19).

The Variable Error

The magnitude of the variable error for current aircraft was estimated by ICAO to increase from 110 feet at 5,000 feet to 250 feet at 30,000 feet and to remain at 250 feet for altitudes up to 50,000 feet.

In an early investigation to determine the variable error for a variety of civil and military aircraft, 96 airplanes representing 31 types were calibrated with pacer aircraft as the calibration reference (ref. 20). The results indicated that at altitudes of 10,000 and 15,000 feet, the differences in the static-pressure errors among airplanes of a type were within 100 feet for 22 types, between 100 and 200 feet for 8 types, and greater than 200 feet for 1 type. For most of the aircraft types, therefore, the variable errors were within the ICAO estimates (130 feet at 10,000 feet and 150 feet at 15,000 feet).

In more recent tests of 16 military transports representing three aircraft types (ref. 21), the variable errors, as determined by a ground-camera technique, were found to be 35 feet at 10,000 feet for one type aircraft, 165 feet at 18,000 feet for a second type, and 105 feet at 35,000 feet for a third type. Since the six airplanes for which the 105-foot error was determined were all comparatively new, the variable error for older airplanes of the same type would be expected to be larger; the 250-foot value estimated by ICAO for an altitude of 35,000 feet would, therefore, appear reasonable.

In another recent investigation of the variable error in France (ref. 22), the results of tests of the first 30 airplanes of a type also confirmed the ICAO estimates.

Calibration Methods

Although estimates have been made of the relative accuracies of various methods for the calibration of static-pressure systems (ref. 23), comparative data on the experimental accuracy of the methods currently being used are lacking. Both ICAO and IATA have, therefore, expressed the need for a universal method to which the calibration of all aircraft could be referenced; a requirement was also stated that the method be simple enough for routine or periodic calibration checks.

During the latter part of 1962, the FAA and the NASA selected and conducted a flight evaluation of a calibration method that appeared to best meet the requirements of accuracy and reproducibility demanded of a primary standard. This method comprised two test procedures, namely, a ground-camera technique for calibrations at low altitudes and a ground-radar technique for calibrations at high altitudes. To determine the accuracy that could be achieved with these techniques, calibrations of a jet transport were conducted using the most precise instrumentation available (ref. 24).

From the results of two flights at heights of about 500 feet and two flights at heights of about 25,000 feet, the standard deviation (σ) of the data from both the low- and the high-altitude tests was found to be about 1/3 pound per square foot. The altitude errors corresponding to this pressure error are 4 feet at sea level and 10 feet at 25,000 feet. For these values of σ and for the test airspeeds for which eight data points were obtained, the mean of the calibration is known, for a confidence level of 99 percent, to be within 5 feet at sea level and 13 feet at 25,000 feet.

On the basis of these results, the instrumentation and techniques used in this investigation are considered suitable for use as a primary standard. However, because the method is expensive as regards radar cost and flight time per data point, there is a need for a simpler, less expensive method for conducting routine calibration checks. Although the ground-camera technique can be used for such check calibrations (as was done in the investigation of ref. 21), the method is not considered sufficiently simple and flexible for use by aircraft operators. Other methods are, therefore, being evaluated by the FAA in an attempt to find an acceptable method that can be used through a wide range of speed and altitude and still provide the precision required of a secondary standard.

Flight Technical Errors

For flight under autopilot control, the flight technical error was considered by IATA to depend on the type of aircraft, the accuracy of the autopilot, and atmospheric conditions (ref. 2).

On the basis of a number of investigations of the flight technical errors of civil aircraft at altitudes up to 25,000 feet, ICAO concluded that the errors were normally distributed and that a value of 500 feet could be assigned as a probable maximum value for civil operations at altitudes up to 50,000 feet. Since it was felt that this figure could be reduced by greater use of autopilots with height lock, an objective was stated for reducing the error to values that would range from 200 feet at 5,000 feet to 325 feet at 50,000 feet.

During the past year, the NASA reported an investigation of the flight technical errors of commercial transports operating under autopilot, altitude-hold control at altitudes up to 40,000 feet (ref. 25). The data were obtained from 19 airplanes (including turbojet, turboprop, and piston-engine types) on 6,421 flights over a variety of routes including transoceanic. The errors were determined from pressure-altitude recordings which were evaluated in terms of the percent of the cruise time the airplanes flew at given altitude deviations from their cruise flight levels.

The altitude deviations for 0.3-percent cruise time (a criterion suggested by the 99.7-percent probability of the 3σ value of a normal distribution) of the 19 airplanes are shown on figure 2 for each of the 5,000-foot-altitude brackets within which the data were collected. This figure shows that the maximum value throughout the 40,000-foot range is 250 feet and that, for most of the airplanes, the values are appreciably lower than those proposed by ICAO as a desirable objective.

An analysis of the distribution of the flight technical errors of reference 25 showed the errors to be random but not normally distributed. Because of the nature of these distributions, the altitude deviations at 0.3-percent cruise time do not always reflect the much larger deviations that were experienced by many of the airplanes. For example, although the altitude deviations for 0.3-percent cruise time of the ten turbojets operating between 25,000 and 40,000 feet were 225 feet or lower, the maximum deviations recorded on nine of the airplanes were in excess of 500 feet; for four of the airplanes the deviations were in excess of 1,000 feet. Furthermore, these relatively large deviations occurred more frequently than might be expected; for example, for the 2,361 flights of the ten turbojets, over 250 deviations greater than 300 feet were recorded. Because of the magnitude and frequency of these large deviations, it would appear desirable to incorporate some form of altitude-deviation monitoring device to alert the pilot whenever the deviation exceeded some specified value, for example, 250 feet.

In view of the quantity of data collected in the NASA investigation, the altitude deviations determined from this study are considered to be representative of those to be expected for civil transports under autopilot altitude-hold control at altitudes up to 40,000 feet. Since the altitude deviations for military and general aviation aircraft may differ from those of the civil transports, investigations of altitude-keeping performance of these aircraft would be required before a complete assessment can be made of the flight technical error.

Combined Errors

As noted earlier, the system error is the combined value of the instrument and static-pressure errors and the altimetry error is the combined value of the system and flight technical errors. Because of the difficulty of measuring either of the combined errors under actual operating conditions, attempts have been made to compute these errors by statistical procedures.

In the calculation of combined errors by ICAO and IATA (refs. 1 and 2), each of the individual errors (instrument, static-pressure, and flight technical) was assigned a probable maximum value and a type of error distribution. The individual errors were then combined by the root-mean-square procedure to produce either a system error or an altimetry error for a single airplane. For an assessment of vertical separation standards, the altimetry errors of two airplanes were combined by the same procedure and the resultant error was considered to represent the loss in vertical separation that would be equaled or exceeded 3 times in 1,000.

System Error

An investigation to determine the sum of the system errors of two aircraft under actual operating conditions was conducted by eleven airlines under the sponsorship of IATA in 1963 (ref. 26). The measurements were made during routine flights over the North Atlantic at altitudes above 29,000 feet. The sum of the errors was determined as the difference between the pressure-altitude separation and the actual height separation (as measured by radio altimeters) of any two aircraft operating within specified space and time limits (e.g., common longitude within navigational accuracy limits, lateral separation within 1/2 degree of latitude, vertical separation within 2,000 feet, and a time separation no greater than 1 hour). From 1,280 pairs of observations, the sum of the system errors of two aircraft was found to be normally distributed and to have a 3σ value of 510 feet. The reliability of this value is, of course, dependent on the accuracies of the radio altimeters and on the degree of concurrency (in terms of both time and position) of the two pressure-altitude readings.

For this 510-foot value for two aircraft, the system error for a single aircraft, computed by the error-combining procedure used by ICAO and IATA, would be 360 feet. Since the flight measurements were obtained with both uncorrected and servo-corrected precision altimeters, only a general comparison can be made between this flight value of 360 feet and the estimates of system errors given in reference 1. For an altitude of 35,000 feet (the assumed average altitude for the flight data), the 3σ value of the system error for a system incorporating an uncorrected precision altimeter was estimated in reference 1 to be 342 feet; for a servo-corrected system, the error was estimated to be 279 feet.

Altimetry Errors

In an assessment of vertical separation standards in 1960 (ref. 2), IATA concluded that 1,000-foot separations were safe and acceptable up to 50,000 feet for aircraft equipped with precision altimeters or instruments with better performance. This conclusion was based on the assumption that the fixed static-pressure error would be corrected (by calibration card) to a residual error of 50 feet, that the probable maximum values of the variable static-pressure error would be those estimated by ICAO (for example, 250 feet for altitudes above 30,000 feet), and that the flight technical error would have a probable maximum value of 500 feet. All of the errors were assumed to have a normal distribution except the residual error of the static-pressure correction, which was assumed to have a rectangular distribution.

For an altitude of 40,000 feet, the instrument and static-pressure errors, according to the IATA estimate, are 249 and 264 feet, respectively. When these errors are combined with the 500-foot flight technical error, the altimetry error for a single aircraft becomes 618 feet. For two aircraft, the statistical sum of the two altimetry errors would be $618 \times \sqrt{2}$ or 874 feet. Graphical representations of the distributions of these individual and combined errors are shown in figure 3a. If the 874-foot value is considered as a measure of vertical separation loss within an assigned separation of 1,000 feet (reduced by 50 feet to account for the vertical size of the aircraft), the actual separation would be 76 feet.

In contrast to this procedure of computing vertical separation loss from a statistical summation of two altimetry errors, the altimetry errors of two aircraft can also be related to a given separation to provide another measure of operational safety, namely, collision probability. In reference 27 it was shown that, if the altimetry-error distributions of two aircraft can be represented by normal curves and if the two curves are separated by an amount equal to the assigned separation, then, if the aircraft are located along a vertical line, the probability of collision is determined by the extent to which the curves overlap and by the vertical dimensions of the aircraft. This procedure for calculating collision probabilities is illustrated in figure 3b for the same set of values used in figure 3a (i.e., altimetry errors of 618 feet, aircraft dimensions of 50 feet, and an assigned separation of 1,000 feet). For this case, the collision probability was calculated to be 192/1,000,000. This, then, is the collision probability that would apply (along a vertical line) when the actual separation, calculated by the vertical separation-loss procedure, is 76 feet.

To indicate the manner in which collision probability varies with altimetry error, additional calculations were made for the case of two aircraft having vertical dimensions of 50 feet and an assigned separation of 1,000 feet. The results of these calculations are plotted in figure 4, which shows the collision probability to be near zero for altimetry errors up to 400 feet, to increase to 10/1,000,000 at an altimetry error of 500 feet and to increase thereafter at a very rapid rate for altimetry errors greater than 500 feet. It should be emphasized that these values of collision probability are relative and that the actual probabilities of collision would be lower if account could be taken of lateral and longitudinal separations.

From a consideration of the flight technical errors determined in the NASA investigation (which showed the altitude deviations for 0.3-percent cruise time to be considerably lower than the 500-foot value assumed in the IATA analysis), it might appear that altimetry errors of 500 feet or less can be realized with present-day equipment.

To examine this possibility, calculations have been made of an altimetry error based on (1) a flight technical error of 225 feet (the highest value determined in the NASA investigation for the altitude range of 25,000 to 40,000 feet), (2) a servo-correction system error of 0.2-percent altitude (assumed to have a normal distribution and to be applicable to both the instrument error and the fixed static-pressure error), and (3) the ICAO assumed value for the variable error of the static-pressure system. For an altitude of 40,000 feet (for which the residual error of the servo-correction system is 80 feet and the variable static-pressure error is 250 feet), the system error would be 262 feet.

Since the flight technical errors determined in the NASA investigation were not normally distributed, they cannot be combined with the 3σ value of a normally distributed system error by the statistical summation procedure used by ICAO and IATA. As an alternate, and more conservative, approach, the two errors have been added directly (as indicated in fig. 5 for two aircraft having an assigned separation of 1,000 feet) to produce an altimetry error of 487 feet.

Since the probability that the system error will be either plus or minus 262 feet is 1.5/1,000, the probability that the actual flight levels of the two airplanes will each be displaced by 262 feet and in directions to reduce separation is 2/1,000,000. Similarly, since an altitude deviation of 225 feet either above or below the actual flight level would occur for 0.15 percent of the cruise time, deviations of 225 feet by both of the aircraft in directions to reduce the separation would occur for 0.0002 percent of the cruise times of the two aircraft.

From a consideration of (1) the low probability of the two flight levels being displaced from the assigned altitudes by 262 feet in directions to reduce separation and (2) the low percent of their cruise times that the two aircraft would each deviate by an additional 225 feet in directions to further reduce the separation, it would appear that the collision exposure time for the two aircraft would be extremely small. The probability of a collision occurrence, however, would be even smaller, since such a condition would require that the altitude deviations of the two aircraft occur over the same point (i.e., with zero horizontal separation).

On the assumption that these values for the system error and the flight technical error are truly representative of the operational accuracies that can be achieved with currently available instruments, autopilots, and aircraft, it would appear that a high degree of operational safety can be realized within 1,000-foot vertical separations at altitudes up to 40,000 feet. However, in view of the large excursions from flight level that were encountered when the altitude deviations for 0.3-percent cruise time were 225 feet or less, it would appear that this degree of safety will be realized only if the aircraft are equipped with altitude-deviation warning devices to insure that the flight technical errors are kept within limits approximating the 225-foot value assumed in this analysis.

Need For Further Work

From the foregoing review of altimetry developments, it is apparent that significant progress has been made in recent years. However, the need for further efforts in some areas has also been indicated.

With regard to static-pressure measurements, for example, there is a need to develop a simple and precise calibration method and to establish an international standard to which the calibrations of all aircraft can be referenced. The development of such a method would provide more accurate corrections for the static-pressure errors of individual aircraft and would permit the accumulation of information on the variable error of the static-pressure systems of large numbers of aircraft.

There is also a need for collecting data on the flight technical errors of military and general aviation aircraft. Because of the large altitude deviations which have been found to occur with aircraft on autopilot altitude-hold control, a need for an altitude-deviation monitoring and warning device has also been indicated.

Finally, there is a need to improve the maintenance practices and to standardize the equipment and procedures relating to the routine testing and installation of the instruments.

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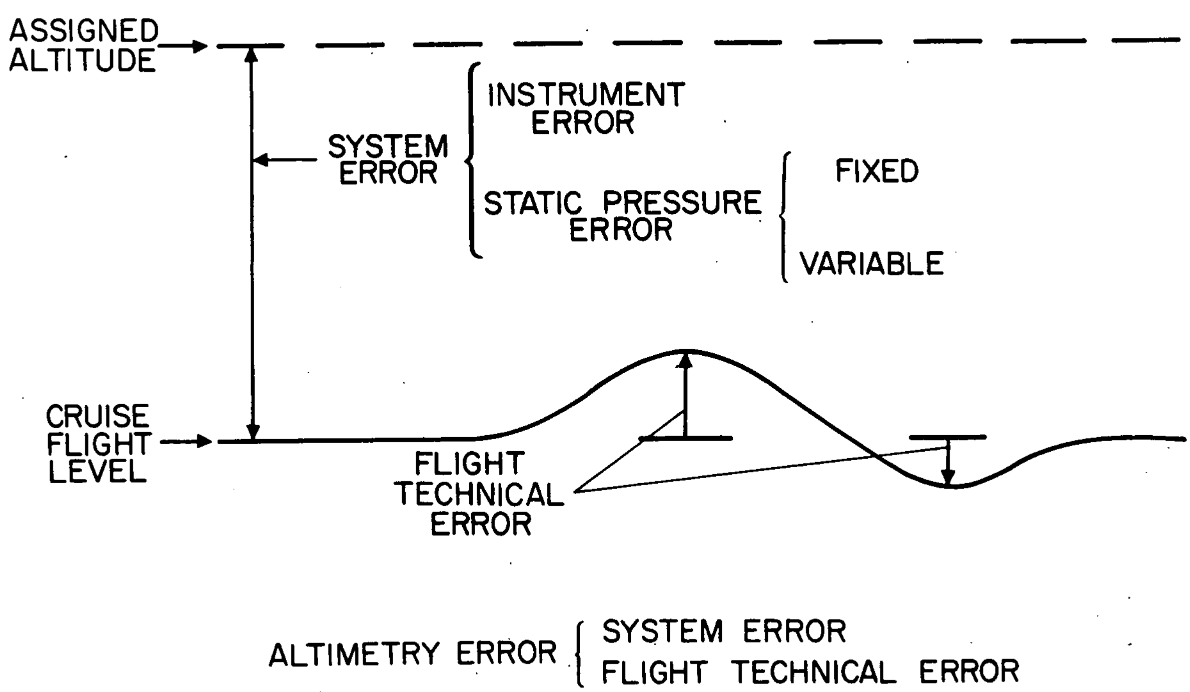


Figure 1.- Pressure altimetry errors.

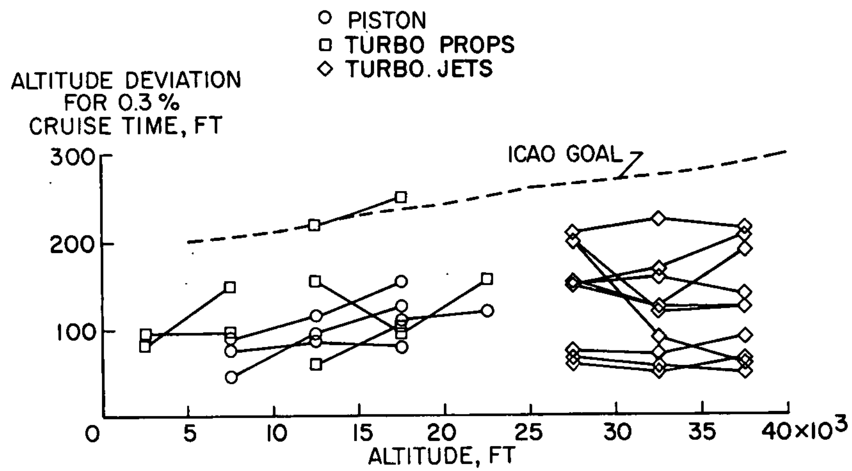
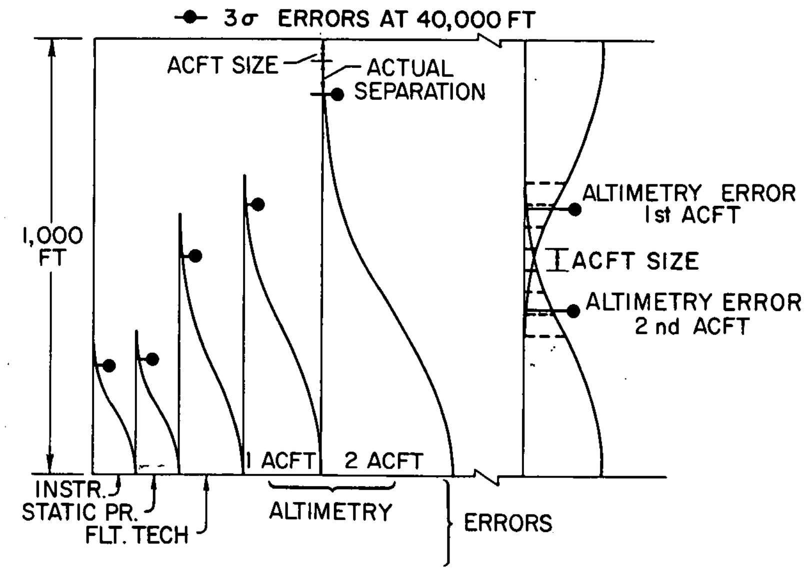


Figure 2.- Flight technical errors of 19 civil transports.



(a) Vertical separation loss.

(b) Collision probability.

Figure 3.- Vertical separation assessment methods.

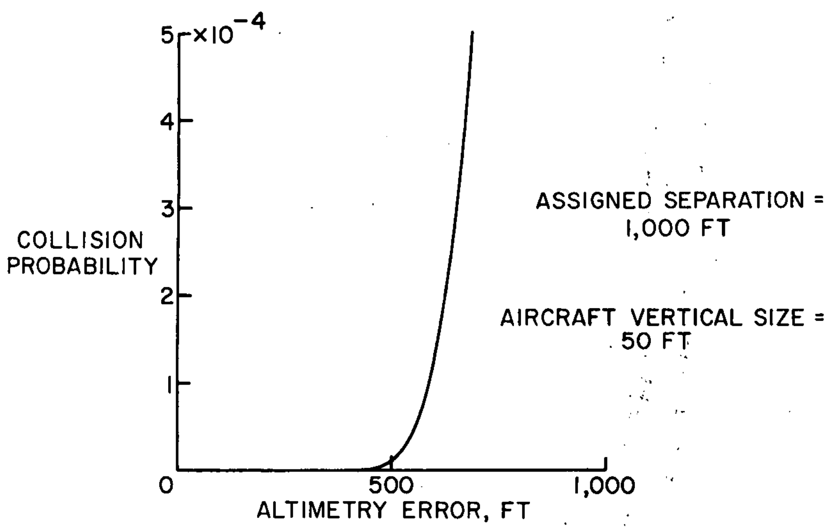


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Figure 4.- Collision probability versus altimetry error.

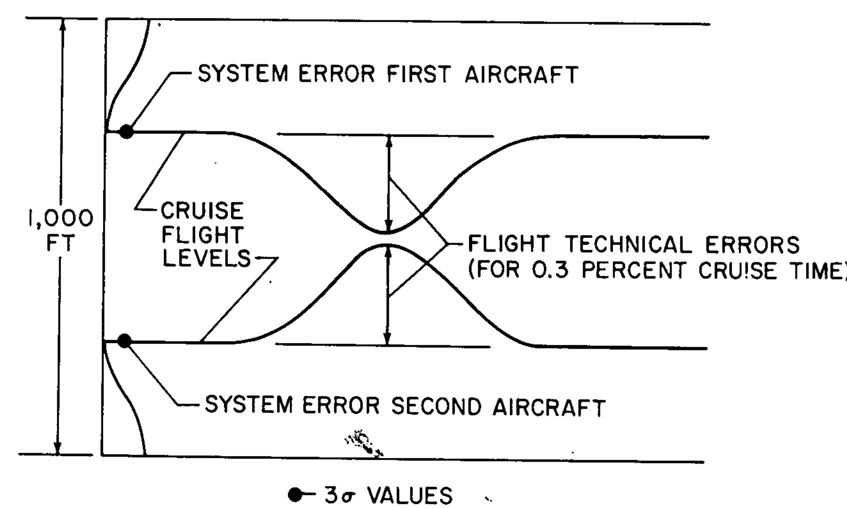

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Figure 5.- Altimetry errors of two aircraft at 40,000 feet.